Efficiency and production yield measurements of radioactive O, N, and F for the SPIRAL facility

S. Gibouin, A.C.C. Villari, J.C. Angélique, O. Bajeat, F. Bocage, J.M. Casandjian, S. Essabaa, G. Gaubert, Y. Huguet, A. Joinet, et al.

Conference Abstract Number: **30**

EFFICIENCY AND PRODUCTION YIELD MEASUREMENTS OF RADIOACTIVE O, N AND F FOR THE SPIRAL FACILITY

S. Gibouin [a, *], A.C.C. Villari [a], J.C. Angelique [b], O. Bajeat [c], F. Bocage [a], J.M. Casandjian [a], S. Essabaa [c], G. Gaubert [a], Y. Huguet [a], A. Joinet [c, d], P. Jardin [a], S. Kandri [a], A. Khouaja [a], F. Landre-Pellemoine [a], C. Lau [c], N. Lecesne [a], H. Lefort [c], R. Leroy [a], C. Marry [a], L. Maunoury [e], D. Nayak [a], J.Y. Pacquet [a], M.G. Saint-Laurent [a], C. Stodel [a]

[a] *GANIL - B.P. 55027 - 14076 Caen Cedex 5 – France*
[b] *LPC - IN2P3 - 14050 Caen Cedex – France*
[c] *IPN - IN2P3 - 91406 Orsay Cedex – France*
[d] *ISOLDE CERN - CH-1211 – Geneva 23*
[e] *CIRIL - rue Claude Bloch - B.P. 5133 - 14070 Caen Cedex 5 - France*

Production efficiencies of radioactive oxygen and nitrogen beams for the SPIRAL target-source system, measured at GANIL on the SIRa test bench, are presented. From the overall efficiency of oxygen, the product between the efficiency of transformation of O into CO and the effusion of CO from the target to the ion source, was deduced. The production yield measurements of oxygen and nitrogen isotopes performed on the SIRa test bench and those of fluorine directly measured on the SPIRAL facility are presented.

PACS codes: 25.70.Mn, 28.60.+s, 29.25.Ni, 29.25.Rm
Keywords: ISOL, Radioactive Nuclear Beams, Target-Ion-Source

[*] Corresponding author. Fax: +33-0-2-31-45-44-21
E-mail: gibouin@ganil.fr

1. INTRODUCTION

Based on isotope separation on-line (ISOL) [1], the SPIRAL facility [2] at GANIL delivers beams of radioactive isotopes. These isotopes are produced by fragmentation of a stable primary beam in the SPIRAL target, diffuse out of it and effuse up to an electron cyclotron resonance ion source (ECRIS), where they are ionised. After their extraction from the source, the radioactive isotopes are selected by a separator magnet before being injected into the cyclotron CIME [3] to get medium energy ions. The first radioactive beam ($^{18}Ne^{4+}$), corresponding to the commissioning of the SPIRAL facility, was sent to the experimental area at the end of September in 2001 [4]. The present target-source [5] system can supply radioactive beams of noble gases, with a dedicated target for He and another one for Ne, Ar and Kr. Furthermore, gaseous isotopes or molecules produced in the target could also be efficiently transported to the ion source, which would allow ionising and post-accelerating alternative radioactive beams.

In particular, oxygen and nitrogen radioactive beams are presently of great interest, mostly for astrophysics, e.g. $^{15}O(\alpha,\gamma)^{19}Ne$ [6] and direct reactions studies, e.g. $^{13}N(p,t)^{11}N$ [7]. The SPIRAL carbon target produces important amounts of oxygen and nitrogen molecules (CO, CO_2, CN, etc.) allowing a fast transfer from the target to the ion source. This phenomenon is well known and was already used to produce radioactive beams at LISOL [8] and more recently at CRC, Louvain-la-Neuve [9]. For a more detailed review of ISOL oxygen beams, see reference [10]. Finally, the oxygen and nitrogen molecules are efficiently ionised in the ECRIS, which is the SPIRAL ion source [11]. Therefore, all ingredients necessary for an efficient production of these elements are present in the SPIRAL target-ion source system.

In this paper, we present the results of production efficiency and production yield measurements of radioactive O and N beams measured at the SIRa [12] test bench, and the production yield of radioactive F directly measured in the SPIRAL production cave. The expected production rates on the SPIRAL facility are also given.

2. EXPERIMENTAL SET-UP

The production efficiencies and production yields of radioactive oxygen and nitrogen beams have been measured on the SIRa [12] test bench at GANIL with the target-source system already developed for the production of radioactive neon, argon and krypton. The target, shown in Fig. 1, is made of a 1 μm graphite microstructure (POCO Graphite industries) in a conic shape with slices of 0.5 mm spaced by 0.8 mm, linked by an axis. It can be heated up to 2450 K by sending a current through its axis (the evaporation rate of carbon becomes important for the target above this temperature) to get a fast diffusion of the produced radioactive isotopes. The target is connected to a compact full permanent magnet ECR ion source (NANOGAN3 [13]). The connection between the target container and the ion source is at room temperature. Therefore, for very reactive elements like oxygen, nitrogen and fluorine, the transport of the radioactive species is possible only if volatile molecules would be synthesized. The chemical nature of the target (carbon) plays an important role in this case.

The overall efficiency ξ of the production processes can be described, for example, for the reactive element O and for this target-source system, as follows :

$$\xi_O = \xi_{O\text{-}CO} \,.\, \xi_{diff}(CO) \,.\, \xi_{eff}(CO) \,.\, \xi_{ion}(O/CO) \,.\, \xi_{trans}(O) \quad (1)$$

The right hand terms of equation (1) respectively represent the transformation efficiency of O into CO, the diffusion efficiency of CO, the effusion efficiency of CO, the ionisation efficiency of O coming from CO and the transport efficiency of O. The product $\xi_{diff}(CO)$. $\xi_{eff}(CO)$ is life-time and temperature dependant, but this is not the case of the product $\xi_{ion}(O/CO)$. $\xi_{trans}(O)$.

For the overall efficiency measurements, we simultaneously implanted secondary ^{14}O and ^{13}N beams, produced by projectile fragmentation using the SISSI device [14,15], in the target of SIRa. The implanted ^{14}O and ^{13}N were identified and quantified by Time-Of-Flight with a plastic detector placed just before the target. Non-ambiguous identification of ^{14}O and ^{13}N were provided at the end of the test bench, by the detection of the 2312.6 keV gamma ray for the first element and the 511 keV rays from β^+ annihilation for the second one, by using a germanium detector. The overall efficiency for each isotope is given by the ratio between their measured quantities at the end of the test bench and those implanted in the production target.

For the production yield measurements, we directly bombarded the SIRa production target with a ^{16}O beam of 95 A.MeV. The quantities of ^{14}O, ^{15}O and ^{13}N were measured, after selection by the separator magnet, at the end of the test bench.

3. EXPERIMENTAL RESULTS

3.1 Efficiency measurements

The different contributions to the overall efficiency of ^{14}O beam production for a target temperature of 2000 K was investigated by measuring the intensities of each molecular compound, as represented in Fig. 2. We assume that the ^{14}O implanted in the target was released under the molecular form CO (due to the enormous quantity of carbon atoms compared with others impurities). The other molecules were presumably created in the plasma of the ion source by a chemical reaction with mainly hydrogen, nitrogen, water, etc. The overall efficiency of ^{14}O found in all charge states and any molecular compounds was equal to 6.5(4) %.

The overall efficiency of ^{14}O beam production, as a function of the target temperature, was also investigated. These measurements are shown in Fig. 3. We can observe that around 2000 K a production plateau is reached. Therefore, one may conclude that for ^{14}O ($T_{1/2}$ = 70.6 s) the diffusion efficiency reached 100 % at this temperature. Concerning effusion, this is not the case, mainly because the transfer between target and ion source is cooled.

Moreover, we performed complementary off-line measurements on the ionisation efficiency of O coming from CO. In this study, a known quantity of stable $^{13}C^{16}O$ was injected through a calibrated valve. The quantity of ionised ^{16}O (including molecular forms) was measured at the end of the separator magnet. The ratio between these two quantities represents the ionisation efficiency of ^{16}O coming from $^{13}C^{16}O$, so-called $\xi_{ion}(^{16}O/^{13}C^{16}O)$. The ionisation efficiency of ^{13}C coming from $^{13}C^{16}O$, so-called $\xi_{ion}(^{13}C/^{13}C^{16}O)$, was also measured and found approximately similar. Therefore, we assumed that both ionisation efficiencies are equivalent, i.e.

$$\xi_{ion}(^{13}C/^{13}C^{16}O) = \xi_{ion}(^{16}O/^{13}C^{16}O) = \xi_{ion}(^{14}O/^{12}C^{14}O) \qquad (2)$$

Considering a total beam transport efficiency of 53(5) % - also measured off-line using a ^{40}Ar calibrated leak - we obtained $\xi_{ion}(^{13}C/^{13}C^{16}O) = \xi_{ion}(^{14}O/^{12}C^{14}O)$ equal to 29(9) %. Finally, one can conclude that for ^{14}O ($T_{1/2}$ = 70.6s) at 2000 K, the product between the transformation efficiency of O into CO and the effusion efficiency of CO between target and ion source is:

$$\xi_{14O\text{-}12C14O} \cdot \xi_{eff}(CO) = 42\ (13)\ \% \qquad (3)$$

Similarly, the overall efficiency for ionisation of ^{13}N was also measured at 2000 K. We obtained 0.67(5) % for $^{13}N^{1+}$, 0.047(8) % for $^{13}N^{3+}$, 0.048(5) % for $^{12}C^{13}N^{+}$ and 0.032(11) % for $^{13}N^{16}O^{+}$. In the case of nitrogen, the CN molecule is not an inert molecule at room temperature like CO. Therefore, the transport of radioactive nitrogen is less efficient.

3.2 Expected production rates on SPIRAL

The production yields of ^{14}O, ^{15}O and ^{13}N were measured at the SIRa test bench impinging a limited intensity of 0.25 pμA of a 95 A.MeV ^{16}O primary beam (corresponding to 380 W) directly on the carbon target, heated at about 2000 K. The average production rates obtained during 2 days of irradiation are presented in Table 1. From these results, we extrapolated the production rates for SPIRAL supposing a maximum beam power of 1500 W of a suitable primary beam (cf. Table 1). A 50 % transmission factor of the SPIRAL separator was assumed, provided that the correct adaptation of the beam to the injection of CIME imposes beam losses. It should be noted that the intensities obtained on-line are in perfect agreement with the estimations using the EPAX [16] model and the efficiencies measured in the preceding session.

^{18}F production yields were also directly measured on the SPIRAL facility by impinging 0.2 pμA of a 95 A.MeV ^{20}Ne primary beam on the SPIRAL target. We obtained 2 x 10^5 p/s at the exit of the CIME cyclotron, corresponding to around 8 x 10^5 p/s just after the ion source. It is expected that with a 1500 W primary beam of ^{19}F, the final production rate of ^{18}F will be around 1 x 10^6 p/s.

4. CONCLUSION

In the framework of SPIRAL developments, the production efficiencies and production yields of radioactive O and N beams have been studied on the SIRa test bench. The overall efficiency measurements of oxygen and nitrogen have been presented, indicating that many molecules are created not only in the target zone but also in the plasma of the ion source. The efficiency of ^{14}O beam production as a function of the target temperature has been determined and its saturation was observed at 2000 K. Finally, the product between the efficiency of transformation of O into CO and the effusion of CO from the target to the ion source has been deduced. This mechanism is responsible for an efficient transport of oxygen from the target to the ion source plasma.

Production yield measurements of oxygen, nitrogen and fluorine isotopes have been presented. The expected production yields for SPIRAL have been extrapolated. The yield measurements are in perfect agreement with theoretical calculations using EPAX model folded by the efficiencies measured in this paper.

REFERENCES

[1] O. Kofoed-Hansen, K.O. Nielson, K. Danske Vidensk. Selk, Medd. 26, N° 7, 1951.

[2] A.C.C. Villari, Nucl. Phys. A693 (2001) 465.

[3] M. Duval, M.P. Bourgarel, F. Ripouteau, IEEE Trans. Magn. 32 (1996) 2194.

[4] A.C.C. Villari et al., this conference.

[5] F. Landré-Pellemoine, PhD thesis, GANIL T 01 03, 2001.

[6] J.M. D'Auria, Nucl. Phys. A701 (2002) 625c

[7] J.M. Oliveira Jr. et al., Phys. Rev. Lett. 84 (2000) 4056.

[8] N. Severijns et al., Phys. Rev. Lett. 63 (1989) 1050.

[9] M. Loiselet et al., CAARI 16, AIP Conf. Proc. n. 576 ed. by J.L. Duggan and I.L. Morgan, (2000) 269.

[10] U. Köster, in Eur. Phys. J. A, in press.

[11] A.C.C. Villari et al., Nuclear Instruments and Methods in Physics Research B126 (1997) 35.

[12] P. Bricault, Proceedings of the 13th International Conference on Cyclotrons and Applications, Vancouver, (1992) edited by G. Dutto and M.K. Craddock, World Scientific, p. 725.

[13] L. Maunoury et al., Proceedings of the 18th International Workshop on ECR Ion Sources, College Station, Texas USA, edited by P. May and E. Ramirez, (1997) p.138.

[14] A. Joubert et al., IEEE Particle Accelerator Conference, San Francisco, USA, Vol. 1 (1991) 594.

[15] N. Lecesne et al., Nuclear Instruments and Methods in Physics Research B126 (1997) 141.

[16] K. Sümmerer and B. Blank, Phys. Rev. C, Vol.61, N°3 (2000) 034607.

Figure captions:

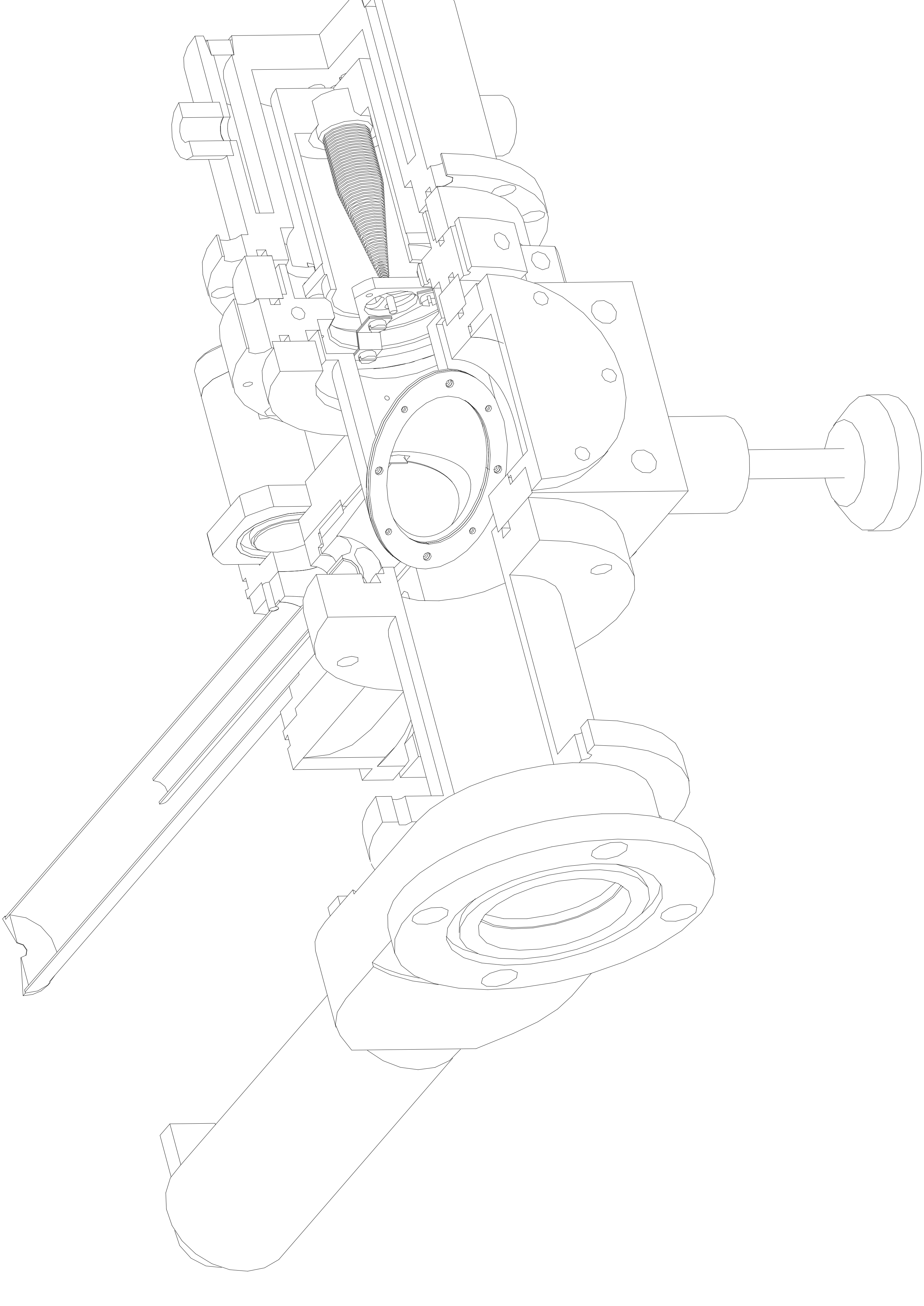
(1) Technical drawing of the Target-Part of the SPIRAL Target-Source production system. The target used for the production of radioactive Ne, Ar and Kr beams is shown.

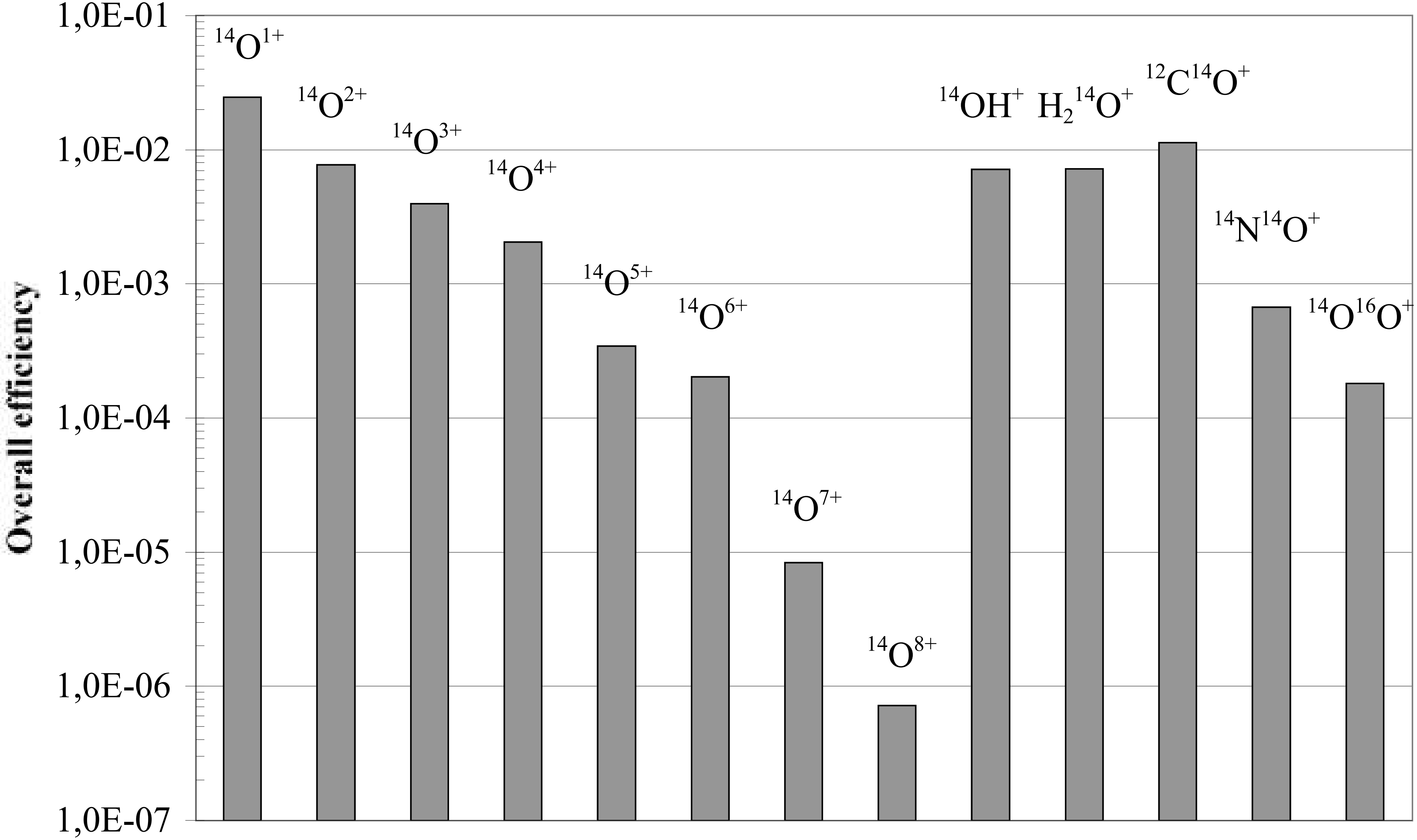
(2) Different contributions to the overall efficiency of ^{14}O measured on the SIRa test bench, for a target temperature of 2000 K. The intensity of the $^{12}C^{14}O^{16}O^{+}$ molecule is not represented because its quantity is negligible compared with $^{12}C^{14}O^{+}$.

(3) Overall efficiency of $^{14}O^{1+}$, $^{14}O^{3+}$ and $^{12}C^{14}O^{1+}$ on the SIRa test bench as a function of the target temperature. A line is drawn to guide the eye.

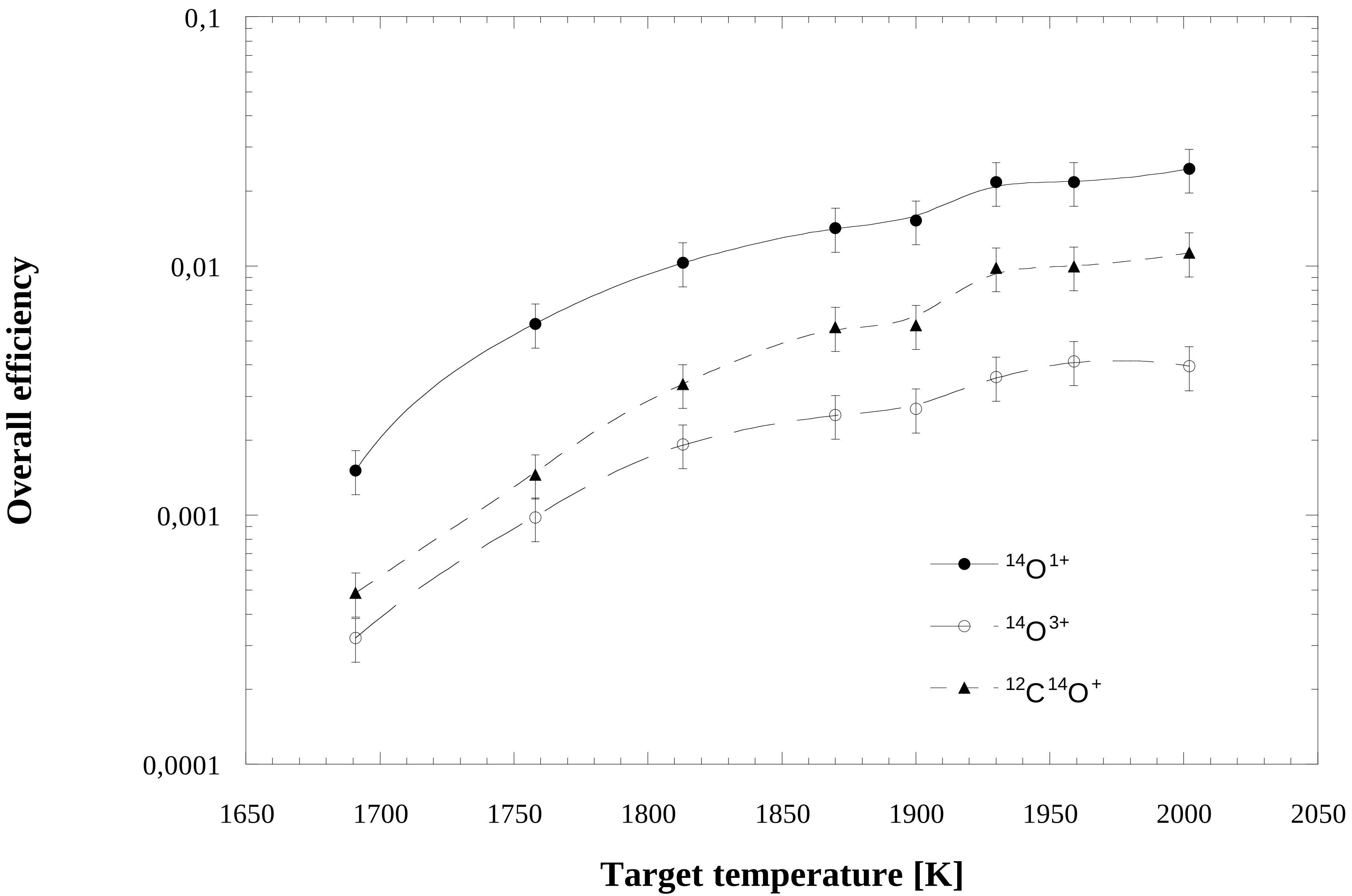
Table caption:

(1) Production yield measurements on the SIRa test bench and production yields extrapolated for SPIRAL when choosing the best primary beam. The $^{15}O^{5\text{-}6+}$ production yield on SIRa has been extrapolated by using the efficiency measurement of $^{14}O^{5\text{-}6+}$.





Overall efficiency
1,0E-01
1,0E-02
1,0E-03
1,0E-04
1,0E-05
1,0E-06
1,0E-07
$^{14}O^{1+}$
$^{14}O^{2+}$
$^{14}O^{3+}$
$^{14}O^{4+}$
$^{14}O^{5+}$
$^{14}O^{6+}$
$^{14}O^{7+}$
$^{14}O^{8+}$
$^{14}OH^{+}$
$H_2{}^{14}O^{+}$
$^{12}C^{14}O^{+}$
$^{14}N^{14}O^{+}$
$^{14}O^{16}O^{+}$



0,1
0,01
0,001
0,0001
1650
1700
1750
1800
1850
1900
1950
2000
2050
Overall efficiency
Target temperature [K]
$^{14}O^{1+}$
$^{14}O^{3+}$
$^{12}C^{14}O^{+}$

ion	primary beam used on SIRa	mean production rate measured on SIRa and normalised by 380W of primary beam	primary beam on SPIRAL	expected production yields at the entrance of CIME
$^{14}O^{1+}$	$^{16}O^{8+}$ 95 A.MeV	7.2 (1.4) 10^{6} p/s	$^{16}O^{8+}$ 95 A.MeV	1.4 (0.3) 10^{7} p/s
$^{14}O^{2+}$		2.2 (0.4) 10^{6} p/s		4.3 (0.9) 10^{6} p/s
$^{14}O^{3\text{-}4+}$		8.4 (1.7) 10^{5} p/s		1.7 (0.3) 10^{6} p/s
$^{14}O^{5\text{-}6+}$		2.2 (0.4) 10^{5} p/s		4.4 (0.9) 10^{5} p/s
$^{15}O^{1+}$		2.3 (0.5) 10^{8} p/s		4.6 (0.9) 10^{8} p/s
$^{15}O^{2+}$		7.0 (1.4) 10^{7} p/s		1.4 (0.3) 10^{8} p/s
$^{15}O^{3\text{-}4+}$		2.7 (0.5) 10^{7} p/s		5.4 (1.1) 10^{7} p/s
$^{15}O^{5\text{-}6+}$		7.2 (1.4) 10^{6} p/s		1.4 (0.3) 10^{7} p/s
$^{13}N^{1+}$		1.4 (0.3) 10^{7} p/s	$^{14}N^{7+}$ 95 A.MeV	5.0 (1.0) 10^{7} p/s
$^{13}N^{2+}$		2.5 (0.5) 10^{6} p/s		9.0 (1.8) 10^{6} p/s
$^{13}N^{3+}$		4.0 (0.8) 10^{5} p/s		1.5 (0.3) 10^{6} p/s
$^{13}N^{4\text{-}5+}$		5 (2) 10^{4} p/s		2 (1) 10^{5} p/s